Can glasses help us to unravel the origin of barred olivine chondrules? Varela, M. E.[1], Kurat, G[2] and Zinner E.[3] [1]CONICET, UNS Dpto Geologia, San Juan 670, 8000 B. Blanca, Argentina, evarela@criba.edu.ar, [2]Institut für Geologische Wissenschaften, Universität Wien, Althanstrasse 14, A-1090 Vienna, Austria, [3]Laboratory for Space Sciences and Physics Department, Washington University, St. Louis, MO 63130, USA.

Introduction: Barred olivine (BO) chondrules are one of the most striking objects in chondrites. Their omnipresence and particular texture caught the attention of researchers and, thus, considerable effort has been put into unravelling their origin(s). Here we report on detailed studies of two BO chondrules and elaborate the prominent role liquids played in their origin.

Results: Chondrule Ess-BO-1 from the Essebi CM2 chondrite (PTS Essebi, NHM, Vienna) is a member of the *Classic type* as defined by [1]. The parallel thin plates of olivine are set into a clear glassy mesostasis and have – as does the thin enveloping olivine crust - uniform extinction (Fig. 1). Clear glass inclusions and neck inclusions (glass inclusions still connected to the mesostasis glass) are present in several of the olivine plates. The olivine crust has irregularly distributed metal inclusions (Ni: 4.3 - 5 wt%). Three small euhedral Ca-rich pyroxenes (< 30 µm in length and 15 µm wide) are present in this chondrule.

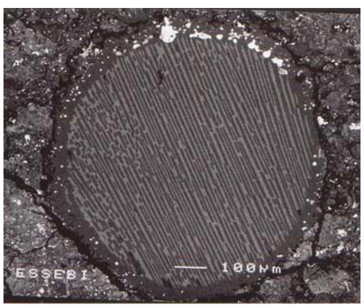

Fig. 1

Chondrule Bishunpur Ch-A from the Bishunpur LL3.1 chondrite (PTS Bishunpur v. G3684 (2), NHM, Vienna) is composed of two olivine crystals which form a core and a thick mantle. The core consists of euhedral to subhedral discontinuous olivine plates and clear glassy mesostasis. The thick mantle consists of olivine in two optical orientations. One of them follows the orientation of the majority of the olivine plates and crystals of the core. One core olivine has a glassy neck inclusion and the mantle olivine contains clear primary glass inclusions, some glass pockets and rounded to sub-rounded former metal-rich inclusions, now altered to Fe-Ni oxides (Fig. 2).

The chemical composition of all glasses (glass inclusion, neck inclusion and the clear glassy mesostasis) in Ess-BO-1 are Si-Al-Ca-rich and similar to one another (Table 1). In Bishunpur Ch-A the primary glass inclusions are also Si-Al-Ca-rich while the neck inclusion and the mesostasis glass are rich in alkalis (Table 1).

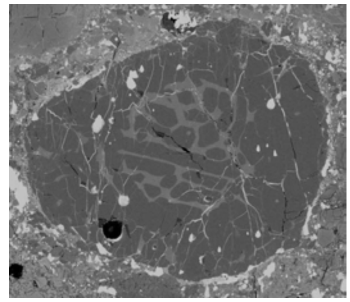
Fig. 2

The mesostasis has a homogeneous chemical composition with minor variations in the Na_2O content (4.36 to 4.98 wt%) and constant K_2O content around 0.2 wt%. Trace element abundances of mesostasis glass in Ess-BO-1 are high (10 – 20 x CI abundances). Olivines in Ess-BO-1 are very similar in composition. From 13 olivines analyzed, 12 vary in their FeO content from 0.60 to 0.74 wt%. Only one spot located near the surface has a high FeO content of 2.2 wt%. Olivines in Bishunpur Ch-A have also a very similar composition with a total range in the FeO content from 0.6 wt% to 1.2 wt% (high value encountered near the surface).

Table 1

Sample	Ess-BO1				Bishunpur Ch-A			
	G.I	N Incl	M.G.	Ol. (13)	G.I	N Incl	M.G.(7)	Ol. (9)
SiO_2	52.6	54.6	53.1	42.2	45.1	59.2	58.7	42.0
TiO_2	0.98	1.23	1.00	0.08	1.05	0.73	0.54	0.03
Al_2O_3	23.6	19.6	23.3	0.17	28.4	17.8	16.8	0.09
Cr_2O_3	0.27	0.32	0.42	0.29	0.27	0.80	0.52	0.23
FeO	0.26	0	0.32	0.80	0.44	0.44	0.95	0.86
MnO	0.01	0.03	0.06	0.04	<0.02	0.04	0.05	0.02
MgO	4.58	3.3	3.95	55.9	4.23	4.27	5.30	56.6
CaO	17.6	20.8	17.4	0.30	20.5	11.0	12.0	0.23
Na_2O	<0.02	<0.02	0.25		<0.02	4.89	4.70	
K_2O							0.2	
Total	99.90	99.90	99.80	99.78	99.99	99.17	99.76	100.06

References: G.I: Glass Incusion; N Incl: Neck Inclusion, M.G (7): Mesostasis glass (mean of 7 analyses)Ol.(13): mean of 13 olivines laths; Ol. (9): average of a 9 spot step scan across a single olivine of the core.

Discussion: The way BO chondrules can form are the topic of ongoing debates. However, there is one point where almost all researchers agree - in particular for the Classic Barred Type - that is, such chondrules must have formed from liquid droplets that were undercooled and crystallized rapidly [e.g., 1-3]. The most popular model has liquid droplets formed by Melting of Solid Precursors (from here on called MSP). The precursors consisted mainly of two components: a refractory and olivine-rich one and a non-refractory and SiO_2- and FeO-rich one [4-6]. For Al-rich BO chondrules a precursor consisting of highly refractory and alkalic materials has also been proposed [7].

An alternative model [8] creates BO chondrules by condensation of olivine plates from the solar nebula (Primary Condensation model - from here on called PC). Following the MSP model, melting temperature must be high and overheating is needed in order to eliminate all crystal nuclei. [e.g., 9-10]. In the case of a classic BO texture only one nucleus has to be present in the liquid droplet that will crystallize one single olivine from the supercooled liquid [11].

Here we suggest a third model that allows creation of BO chondrules directly from the solar nebula by Primary Liquid Condensation (from here on called PLC). In contrast to all other models, the PLC model does not need a re-heating event but utilizes the ability of dust-enriched solar nebular gas to directly condens a liquid [12, 13]. Such liquids are predicted to have a refractory CMAS composition. Our studies of different types of glasses in meteorites (CC, OC, EC and achondrites [14-16]) showed that such liquids must have been omnipresent in the solar nebula. They apparently played an important role by facilitating condensation of the major minerals from the solar nebula gas [16, 17]. Because liquids can nucleate from the vapor much more easily than crystals, the first condensate to appear in the solar nebula is likely to be a liquid. This liquid is predicted to be rich in refractory elements and olivine component. At a high enough degree of undercooling, nucleation and growth occur simultaneously and a plate dendrite will form. The residual liquid (the mesostasis glass precursor) will be rich in refractory incompatible elements - as is observed. The Ess-BO-1 chondrule could have formed in this way. Regarding its chemical composition, Ess-BO-1 is pristine. Its glass mesostasis is Si-Al-Ca rich, has a solar Ca/Al ratio, no traces of alkali elements (Na, K, Rb) and high (10 – 20 x CI) and unfractionated trace element abundances. The bulk chemical composition of Ess-BO-1 (SiO_2: 46.3 wt%, MgO: 39,1 wt%, Al_2O_3: 7.2 wt%, CaO: 6.7 wt%) can be taken as to represent that of a primary condensate liquid and fits the liquid composition predicted by [12, 13].

To form Bishunpur Ch-A apparently takes some more steps. First, its shape is not that of a droplet and, second, its bulk composition is extremely olivine-rich, a composition which is not likely that of a liquid. On the other hand, the BO core documents a liquid and a crystallization history similar to that of Ess-BO-1 but with two olivine nuclei. In addition, glass inclusions in the mantle olivine document the presence of a liquid during its formation. However, the glasses in the core and in the olivine mantle have different compositions: glass inclusions in olivine have CMAS composition but the mesostasis glass of the core is alkali-rich. Independent of the model applied, the remnant liquids in the mantle and in the core should have similar compositions.

Apparently, Bishunpur Ch-A behaved as an open system and the mesostasis has obviously suffered alteration: addition of SiO_2 and replacement of Ca by alkali elements (Na, K). The isolated glass inclusions kept their memory on the original refractory liquid that helped to grow the olivine. The non-spherical shape of Bishunpur Ch-A and its very high olivine content argue against formation from a completely liquid droplet. In contrast, the core is perfectly round – which cannot be expected, if it formed from the residual liquid that produced the mantle olivines – and it has a BO texture, indicating an origin from an all-liquid droplet.

This situation forces us to suggest another, simple, formation history for this chondrule: The BO core formed from an undercooled liquid droplet primary condensate by simultaneous crystallization of two nuclei. Once the core had been formed, both crystals forming the BO shell continue to grow epitaxially from the vapor, supported by a thin liquid layer – something like the vapor-liquid-solid (VLS) growth process [see, e.g., 18, 17, 15] or liquid-phase epitaxy. If we correct for the metasomatic alterations, the core of Bishunpur Ch-A, had originally a bulk chemical composition of: SiO_2 - 43.6 wt%, Al_2O_3 – 11.3 wt%, MgO – 36.5 wt% and CaO – 8.5 wt% - comparable to that of Ess-BO-1 and to that of liquids predicted to condense from a gas of dust-enriched solar composition [e.g., 12, 13].

Conclusion:

Phase compositions in well-preserved primitive BO chondrules suggest a possible formation via nebular liquid condensates and subsequent undercooling and crystallization. Complex BO chondrules and BO inclusions in chondrules and aggregates could have formed in the same way but experienced continuous epitaxial growth of mantle olivine and/or aggregation. This is the same process we previously suggested to have crystals grown from the solar nebular: the liquid-supported condensation process [16, 17].

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